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H. B. Hammel[1,*], I. de Pater[2], S. G. Gibbard[3], G. W. Lockwood[4] , K. Rages[5]

[1] Space Science Institute, Boulder, CO 80303, USA.

[2] Astronomy Department, University of California, Berkeley, CA 94720, USA.

[3] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.

[4] Lowell Observatory, Flagstaff, AZ 86001, USA.

[5] SETI Institute, Mountain View, CA 94043, USA.

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* Corresponding Author.

Email address: hbh@alum.mit.edu

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Editorial correspondence and proofs should be directed to:
Dr. Heidi B. Hammel
Space Science Institute
72 Sarah Bishop Road
Ridgefield, CT 06877

hbh@alum.mit.edu
203-438-3506

Abstract

On 4 July 2004 UT, we detected one of Uranus' southern hemispheric features at K' (2.2 μm); this is the first such detection in half a decade of adaptive optics imaging of Uranus at the Keck 10-m telescope. When we observed again on 8 July UT the core had faded, and by 9 July UT it was not seen at K' and barely detectable at H. The detection and subsequent disappearance of the feature indicates rapid dynamical processes in the localized vertical aerosol structure.

Keywords: Uranus, Atmosphere

1. Introduction

In 1994 the Hubble Space Telescope (HST) turned to the uranian system to search for faint satellites (Zellner et al., 1994). The serendipitous discovery of discrete clouds on Uranus in ring-search images revitalized interest in the planet's atmosphere (Hammel, 1997), which had been muted since the Voyager Uranus encounter showing little atmospheric activity (Smith et al., 1986). Ground-based images from the NASA Infrared Telescope Facility (IRTF) in 1995 resolved the disk, but discrete features were not detected (Baines et al., 1998). Beginning in 1997, however, HST observed Uranus with both the Near-Infrared Camera and Multi-Object Spectrograph (NICMOS) and the Wide Field Planetary Camera 2 (WFPC2), revealing many atmospheric features (Karkoschka, 1998; Karkoschka, 2001; Hammel et al., 2001; Hammel et al., 2004). By 1999, improvements in IRTF image quality permitted detection of a few features in the planet's northern[1] hemisphere (Forsythe et al., 1999; Sromovsky et al., 2000). Since 2000, Uranus has been a target of the W. M. Keck II 10-m telescope on Mauna Kea, Hawaii, using adaptive optics (AO) imaging (de Pater et al., 2002; Hammel et al., 2001; Hammel et al., 2004).

Over the past decade, the inventory of discrete cloud features on Uranus has grown, though some have argued this is due to wavelength choice or changes in viewing angle (e.g., Karkoschka, 2001). During a four-night run in October 2003, over three dozen features were seen in Keck Uranus images (Hammel et al., 2004). None of the 11 features seen in the southern hemisphere in 2003 was detected at K', even though some of these southern features were among

[1] We use the IAU convention for defining the pole position, where the southern hemisphere has been pointing toward the Sun and Earth for the past few decades.

the largest and most easily observed features on the disk at shorter wavelengths. Indeed, no southern-hemisphere features have *ever* been detected at or longward of 2.0 μm (Karkoschka, 2001; Hammel et al., 2001; de Pater et al., 2002; Hammel et al., 2004) until now. We report here the first detection at K' of a discrete southern-hemisphere feature on Uranus.

2. A Surprising Observation on the 4th of July

We obtained images of Uranus on 3, 4, 8, and 9 July 2004 UT using the 10-m Keck telescope with the NIRC2 camera. The AO system produced spatial resolutions of ~0.05" (about 700 km at Uranus). We obtained three sets of images each night, where a set typically contained three exposures each at J, H, and K'. Characteristics of the filters are given in Table 2 of Gibbard et al. (2004). Images were navigated and features located using the procedures described in Hammel et al. (2001, 2004).

On 4 July, a bright feature—dubbed 2004-A—was detected in the southern hemisphere of

Fig. 1 Uranus at latitude –36.0° ± 0.4° (Fig. 1 and Table 1). In H-band images[2], feature 2004-A bore a

Table 1 superficial resemblance in overall size and extended nature to features near this latitude in previous years (e.g., s4 in de Pater et al., 2002; 2000-6 and 1994-2 in Hammel et al., 2001; 2003-

[2] We discuss and show only H-band (1.6 μm) images, but J-band (1.2 μm) data were also obtained on all nights. Because they are similar in appearance to the H-band data, they are not included in this note, but each reference to "H-band" should be understood to mean "H-band and J-band".

A and 2003-N in Hammel et al., 2004). None of those features was detected longward of 2 μm. To our astonishment, feature 2004-A was easily detected at K'.

We obtained images for several more hours on 4 July as the feature transited the disk, and determined that the K' feature was co-located with a condensed core that was significantly

Fig. 2 brighter than the surrounding extended feature in the H-band images (Fig. 2). Features near this latitude in earlier years have been measurably extended at H, with sizes noticeably larger than a resolution element, but have never exhibited a distinct bright core as is seen in these 2004 images (de Pater et al., 2002; Hammel et al., 2004).

3. More Surprises a Few Days Later

When we observed Uranus again on 8 July UT, the feature was again visible at K', but had faded (contrasts are listed in Table 1). The core was still present in H-band images. By 9 July, we were unable to detect the feature at K'; at H the extended feature was seen but the core was barely detected (if detected at all). The relevant 9 July data were taken at moderate airmass (ranging from 1.78 to 1.63) and also as the feature was rotating off the disk. Nevertheless, had the feature been as bright as seen on 4 July, it would have been easily detected.

As Fig. 2 indicates, the overall "feature" in fact had two distinct components, the condensed core (hereafter 2004-A) and the larger complex conglomeration of extended material seen in H. The two components have different zonal velocities (discussed below), with the southern core (2004-A, with latitude –36.0° ± 0.4°) drifting eastward underneath the northern extended feature (2004-B, with an estimated central latitude at approximately –33.7° ± 0.4°). K' images on the 4th hint at extended reflectivity from 2004-A oriented up toward the "middle" of the H-band feature 2004-B (Figs. 2a-2c). However, residual structure in the wings of the point-spread function

(PSF) may also cause such extended brightness. Image deconvolution is planned for these data, and should help resolve whether this extended reflectivity is cloud material or residual PSF.

4. Characteristics of features 2004-A and 2004-B

Velocities. Given the interval between the 4 and 8 July observations and point-like nature of 2004-A, we were able to determine the bright core's zonal wind velocity with high accuracy: 103 ± 2 m/s. Determining a velocity for the northern H-band feature 2004-B was challenging due to its extended nature, but that was mitigated somewhat by the 4-day baseline; a preliminary estimate for this feature was 112 ± 3 m/s.

There have been no published Keck or HST features at –36.0° except the poorly sampled 1994 measurements at latitude –35° ± 1° deg with a highly uncertain velocity of 145 ± 54 m/s (Hammel et al., 2001). The closest well-determined features on record are from Voyager: 1986-4 at -35.2° ± 0.3° with velocity 120 ± 2 m/s, and 1986-5 at -37.7° ± 0.3° with velocity 115 ± 2 m/s (Smith et al., 1986; Hammel et al., 2001). The nearest Keck/HST feature, 2003-A, was located at -37.7° ± 0.7° with velocity 131 ± 17 m/s (Hammel et al., 2004). The 103-m/s velocity of 2004-A is somewhat slower than the velocities of these features.

Regarding feature 2004-B at –33.7° ± 0.4°, the features with comparable latitudes in the past are: the aforementioned Voyager feature 1986-4 at -35.2° ± 0.3° with velocity 120 ± 2 m/s (Smith et al., 1986; Hammel et al., 2001); HST feature 1997-J at –30.8° ± 0.5° with velocity 76 ± 1 m/s (Karkoschka 1998); and Keck features 2003-N at –31.0° ± 0.6° with velocity 75 ± 6 and 2003-R at –31.5° ± 0.6° with velocity 69 ± 6 (Hammel et al., 2004). Feature 2003-N was highlighted by Hammel et al. (2004) as showing complex extended structure. Assuming the usual trend of increasing velocity with increasing southern latitude, the 112-m/s velocity of 2004-B is reasonably consistent with the velocities of nearby features. One interesting note:

2004-A is moving eastward faster than 2004-B, even though it is at slightly higher southern latitude, which is the opposite of the usual trend. Such a reversal was seen only once before, with the two Voyager measurements near these latitudes cited above (1986-4 and 1986-5).

No features have been reported at these two latitudes to date. Either 2004-A and 2004-B are completely new features or else they are long-lived features (2003-A? 2003-N?) that have changed their velocities as they drifted in latitude. Such behavior is not unheard of: indeed, several features on Neptune "wandered" in latitude with concomitant velocity changes (Hammel et al., 1989; Sromovsky et al., 1993). Additional observations of Uranus will undoubtedly discriminate between the two possibilities.

Altitudes, Variability, and Lifetime. The initial high brightness of 2004-A relative to the planetary disk at K' indicates that the scattering particles in this condensed core reach altitudes higher than the 1-bar level; for a discussion of the assumed atmospheric model, see de Pater et al. (2002). The bulk of the material that comprises the larger feature at H (2004-B) is not detectable at K' (Fig. 2), suggesting it lies below the 1.1-bar level (de Pater et al. 2002).

The dimming of 2004-A on the 8th and 9th could be interpreted as subsidence of the feature's cloud tops, since 2004-A still appears to be a point source (i.e., spreading, shearing, or extension is not seen). However, the feature is not resolved, thus we cannot know what is happening at scales smaller than our resolution capability. The data hint, but cannot confirm, that the feature's K' brightness increase was caused by longitudinal proximity of two features at two latitudes. In other words, when 2004-A approached 2004-B, some kind of interaction between the features may have created a vertical disturbance resulting in the elevated K' reflectivity, which faded as 2004-A finally drifted away from the northern feature a few days later.

No K'-bright feature was detected in Uranus' southern hemisphere in October 2003 based on Keck images with excellent spatial and temporal resolution. Thus the lifetime of this activity associated with 2004-A must be shorter than 9 months. How long do they actually last? How often do such K'-bright features appear? Only more observations can address such questions.

5. Summary

This is the first detection of a southern-hemispheric feature at K' on Uranus. The southern hemisphere of Uranus has been observed with complete longitudinal coverage at these wavelengths with this telescope for many years (Hammel et al., 2001; de Pater et al., 2002; Hammel et al., 2004). We concede the possibility that such features come and go. However, other explanations advanced for variations in cloud detections—viewing geometry change, wavelength choice, varying spatial resolution, S/N (Karkoschka, 2001)—cannot account for the lack of past detections of such a southern hemispheric feature using this telescope and filter.

A statistical assessment of past cloud apparitions on Uranus—assuming only changes in viewing geometry of an otherwise "static" planet—led to the conclusion that "the visible activity of Uranus is predicted to increase to approximately 6 southern and 30 northern clouds in 2007..." (Karkoschka, 2001). In 2003, Keck images had revealed over 11 trackable southern features and 19 trackable northern features, and there were more that were not trackable (Hammel et al., 2004). To this we now add the K' southern feature, something never before seen. Together, these observations indicate that current southern activity on Uranus may be higher than the static assumption would imply. Other models suggested that most activity related to seasonal change at this equinox should appear first in the northern hemisphere, if at all (e.g., Friedson and Ingersoll, 1987). Evidence for change can indeed be seen in the planet's northern hemisphere (e.g., Fig. 1d), where activity continued to evolve near the expected latitude of a “northern collar” as predicted by Hammel et al. (2004).

The observations presented here provide a clear example of the dynamic nature of the atmosphere of Uranus. Are we at the beginning of a period when such K’-bright features will become more common, suggesting that such variability is linked to the extreme variations of insolation caused by the planet's unusually large obliquity? That will undoubtedly remain a matter of heated debate, but the growing bulk of the observational evidence is inexorably pushing Uranus from the category of "boring and unchanging" to "interesting and variable." Continued observations of Uranus are strongly encouraged as its 2007 equinox approaches.

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Table 1

Selected Uranus atmosphere images in 2004[a], along with contrast and I/F for feature 2004-A

Panel	Date	Filt[b]	UT Start	Contrast[c,d]	I/F[d,e]	Filt[b]	UT Start	Contrast[c,d]	I/F[d,e]
Fig. 1a	4 Jul	H	11:21:22	0.9	0.025	K'	11:52:04	3.2	0.00069
Fig. 1b	"	"	13:00:43	1.0	0.026	"	13:21:45	4.5	0.00091
Fig. 1c	"	"	15:03:14	1.4	0.030	"	15:23:55	2.9	0.00069
Fig. 1d	8 Jul	H	13:25:39	0.8	0.023	K'	13:45:10	1.0	0.00035
Fig. 1e	"	"	14:54:51	0.5	0.019	"	15:15:31	1.5	0.00035
Fig. 1f	9 Jul	H	10:35:19	0.2	0.015	K'	10:50:59	<0.9 [f]	<0.00026[f]

[a] Data from 3 July are not shown because feature 2004-A was not visible during our observing window that night. Images are shown in Fig. 1; rectilinear maps of Feature 2004-A extracted from the images are shown in Fig. 2.

[b] All H-filter integration times were 60 seconds; K'-filter integration times were 120 seconds.

[c] Peak contrast was defined $DN_{feature}/DN_{background} - 1$, where $DN_{feature}$ is the feature's single brightest pixel and $DN_{background}$ is the mean background value at that latitude. Since the feature was not resolved, the actual contrast is probably higher.

[d] Since the feature was not resolved, the actual contrast and I/F values are probably higher. These "peak" values are provided for comparative estimates of night-to-night variation (the values have not been corrected for viewing geometry).

[e] Wavelength-dependent conversion factors for peak I/F were derived from observations of photometric standard star HD 201941.

[f] In the K' case on 9 July, the contrast and I/F values correspond to a single bright pixel which is probably statistical noise; in actuality, the feature appears much fainter than these values would indicate (see Figs. 1 and 2).

FIGURE CAPTIONS

Fig. 1. Keck images of Uranus in 2004. Here we show a representative sample of those images that contained features 2004-A and 2004-B (circled in each image); times are provided in Table 1. For each pair, the upper image is H (1.6 μm) and the lower image is K' (2.2 μm). The south pole of Uranus is oriented to the left. Images from 4 July are in the top row (a, b, and c). Images from 8 July are the left and middle columns of bottom row (d and e). Images from 9 July are the right-most pair of the bottom row (f). K' images are dominated by ring flux (to be discussed in a different paper). At K', uranian satellites often masquerade as northern cloud features. We indicate some interlopers with arrows and letters: P=Portia (twice), D=Desdemona, and C=Cressida. Subtle variations in the point-spread function can push faint features below the detection threshold. The dark splotches in the panel c image at K' are an artifact caused by residual charge in the detector.

Fig. 2. Maps of features 2004-A and 2004-B. Each re-projected rectilinear map covers 60° in longitude and 20° in latitude, has north up and east to the left, and is centered on the condensed bright core 2004-A, except for panel f where the map is centered on 2004-A's expected location. The panels are as defined in Fig. 1 and Table 1. Feature 2004-A's position relative to more extended material to the north (2004-B) changes between 4 July (a-c) and 8 July (d, e) due to latitudinal variation of zonal velocity. The maps in panels e-f have had a harder stretch applied in order to show feature 2004-A effectively (notice the background atmospheres appear brighter).

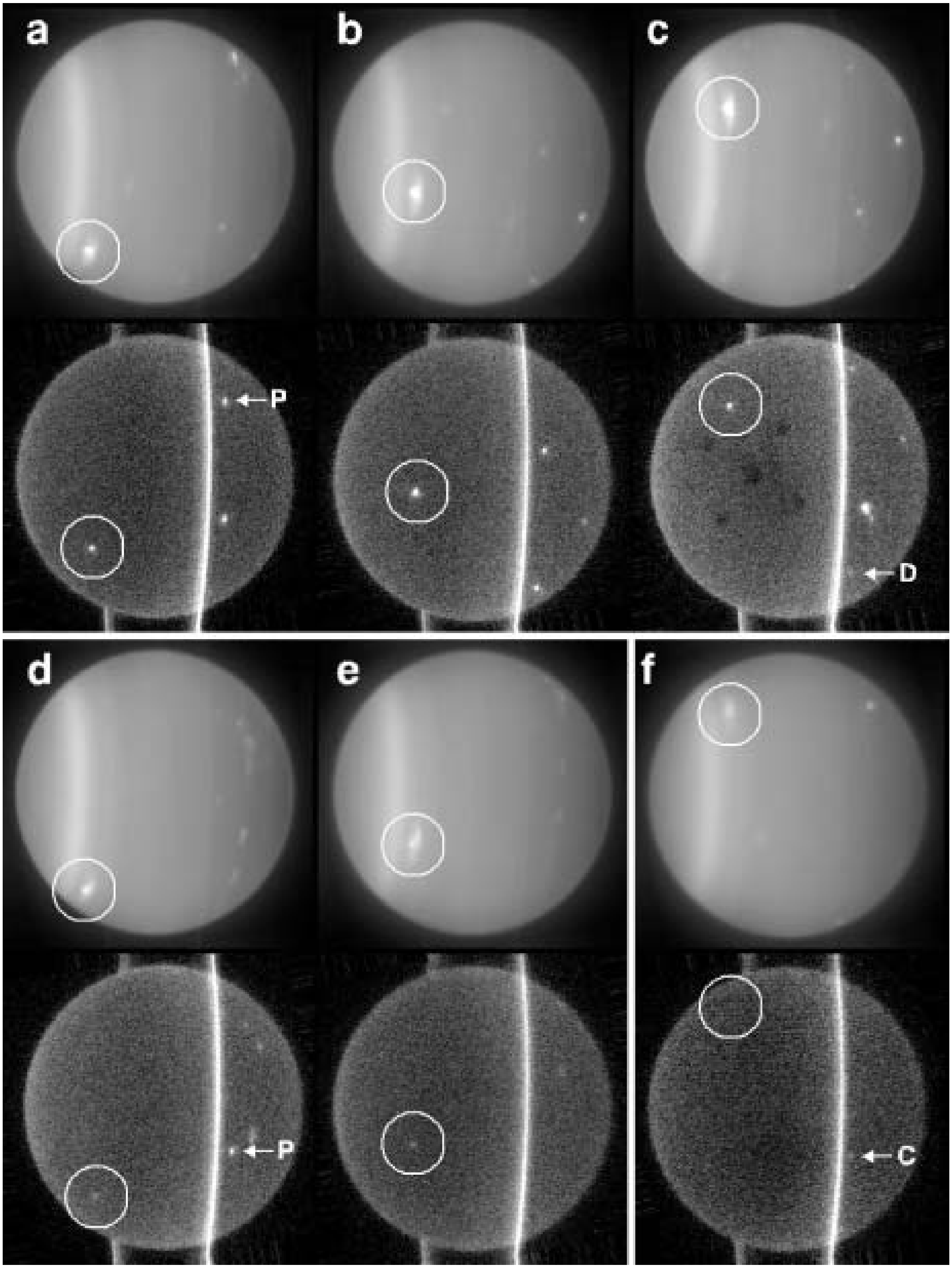

FIGURE 1

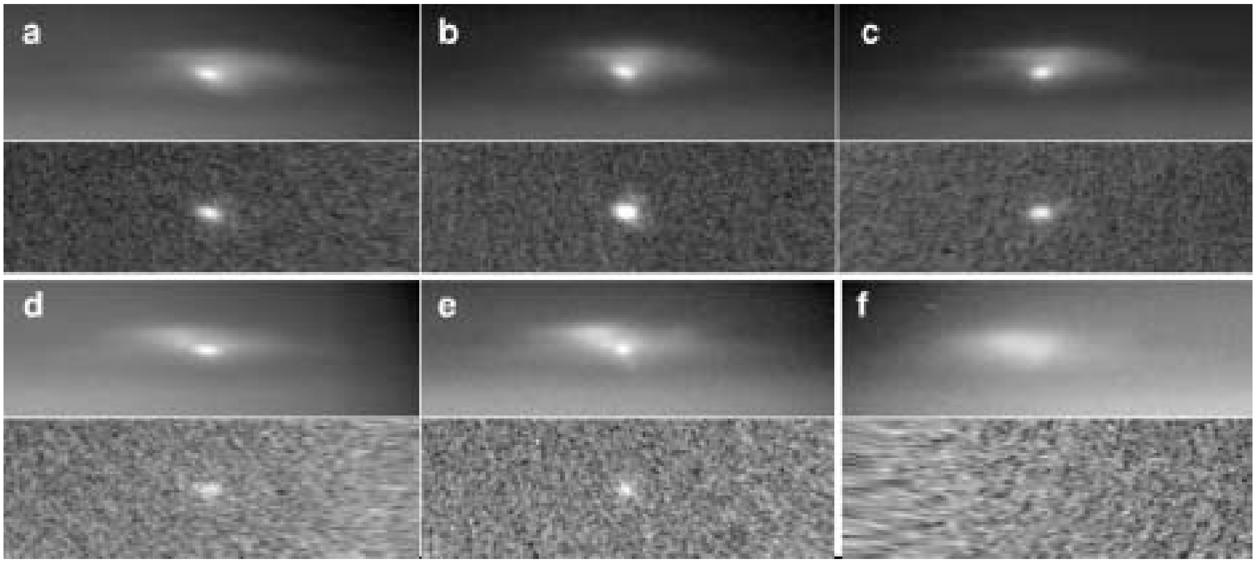

FIGURE 2